Automatica 63 (2016) 101–115

Contents lists available at ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

Infinite-dimensional decentralized damping control of large-scale manipulators with hydraulic actuation[☆]

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ARTICLE INFO

Article history:
Received 16 May 2014
Received in revised form
9 March 2015
Accepted 28 September 2015

Keywords:
Flexible link manipulator
Hydraulic actuators
Concrete pump
Feedback control
Distributed-parameter systems
Passivity
Euler–Bernoulli beams

ABSTRACT

The control design for decentralized active damping of large-scale manipulators with hydraulic actuation is considered in a distributed-parameter framework. The concepts of modern light-weight construction enable the production of machines like mobile concrete pumps or maritime crane systems with extended operating range and less static load. However, due to the reduced weight the elasticity of the construction elements has a significant influence on the dynamic behavior of the boom. In this paper, a modular decentralized control strategy is presented and the asymptotic stability of the closed-loop system is rigorously proven in the infinite-dimensional setting. The proposed damping control strategy features a robust behavior since it is independent of the number and pose of the boom segments and of the exact knowledge of the system parameters. At the end, the practical implementation of the control strategy is discussed and validated by means of measurements on an industrial mobile concrete pump with four joints and an operating range of about 40 m.

1. Introduction

Modern large-scale manipulators such as mobile concrete pumps have a significantly reduced weight compared to classical designs. This is mainly caused by new materials and techniques in construction and production and enables a higher operating range as well as reduced static load. Since at the same time the stiffness of these systems is reduced, they are prone to vibrations, which make the operation more difficult and may lead to the accelerated fatigue of the construction material. For this reason, the development of modern control strategies for active vibration damping or trajectory planning is a topic of current research.

In the literature, many contributions to the modeling of flexible multi-body systems can be found. The existing methods are well developed and are presented in several text books, e.g., Bremer (2008), Shabana (2005) and many others. The modeling of flexible structures in general leads to a mathematical description in form of partial differential equations, which are also referred to as distributed-parameter systems. Most of the investigations related to control strategies for flexible multi-body systems deal with electromechanical actuation. In this context, comprehensive literature can be found, which in part is summarized for example in Tokhi and Azad (2008) and Wang and Gao (2003). For such systems, usually a cascaded control structure with fast current controllers in the innermost control loop justify the assumption that the joint torques serve as control inputs to the system. In contrast, for large-scale manipulators like mobile concrete pumps, hydraulic actuators comprising hydraulic cylinders and valves are commonly used. Their dynamic behavior and the nonlinear characteristics have to be considered in the controller design. The combination of flexible multi-body systems and hydraulic actuators has been studied, e.g., in Henikl, Kemmetmüller, Bader, and Kugi (2015) and Lambeck, Sawodny, and Arnold (2006). Therein the modeling of the flexible structure is typically based on a finite-dimensional approximation of the beam deflection. This approach has the advantage that the equations of motion can be derived in a straightforward way by means of computer algebra programs. However, the distributed-parameter nature of the system is lost in the finite-dimensional model. In Zimmert, Pertsch, and Sawodny (2012), a control design considering the infinite-dimensional model of a flexible turntable ladder is presented. However, the

☆ The authors gratefully acknowledge the financial support by TTControl GmbH and the Austrian Research Promotion Agency (FFG), Project No. 2426433. The material in this paper was not presented at any conference. This paper was recommended for publication in revised form by Associate Editor Nicolas Petit under the direction of Editor Miroslav Krstic.

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http://dx.doi.org/10.1016/j.automatica.2015.10.024
0005-1098/

Fig. 1. Mobile concrete pump with four joints.

considered system can be described by only a single rotating beam and the proposed approach is not designed for a multi-body system.

This paper is motivated by the desire to design a modular advanced damping control strategy for modern mobile concrete pumps as depicted in Fig. 1. In particular in view of the practical relevance, we strive for a control strategy that is independent of the number and pose of the boom segments and does not rely on the exact knowledge of the physical parameters. Basically, the design of the damping controller is based on the linearization of the distributed-parameter system around an arbitrary operating point. This is justified by the fact that the movement of the boom, which is manually controlled by the machine operator, is rather slow.

The control design for distributed-parameter systems is commonly classified into two systematic approaches: In the *early lumping* approach, the distributed-parameter system is first approximated by a finite-dimensional model. Based on this approximation, a controller is developed utilizing well-established design techniques for finite-dimensional systems. However, neglecting the distributed-parameter nature can cause a reduced control performance or even the destabilization of the system due to the well known *spillover*-effects (Balas, 1978). On the other hand, in the *late lumping* approach the infinite-dimensional system dynamics are explicitly taken into account in the controller design, see, e.g., Curtain and Zwart (1995), Luo, Guo, and Morgül (1999) and Rahn (2001). In particular, methods for vibration damping, which *passivate* the closed-loop system, are quite effective, see, e.g., Luo et al. (1999). In this context, the proportional output feedback ensures the dissipativity of the closed-loop system in the case of a so-called *actuator–sensor-collocation*. Here, the control inputs and the output variables build a dual pair of power variables. Numerous results are available for single rotating and clamped beams, see, e.g., Kugi, Thull, and Kuhnen (2006), Luo (1993), Luo et al. (1999) and Shifman (1993). In particular, in Luo (1993) and Luo et al. (1999) the feedback of the beam deflection in combination with a velocity controlled servo motor is analyzed. Therein, the exponential stability of the closed-loop system is shown. Since it is well known that a velocity control for a hydraulic cylinder piston can be simply realized by means of a servo compensation, this is of special interest in the considered application.

For the damping control of flexible structures with more than one beam, only a few results are available in the *late lumping* setting. The main reason for this is that the derivation of the associated, in general highly nonlinear, partial differential equations is rather complex. An example is given in Zhang, Xu, Nair, and Chellaboina (2005), where the nonlinear infinite-dimensional model of a flexible robot with two beams is considered. In Lagnese, Leugering, and Schmidt (1994), a general approach for the infinite-dimensional modeling and analysis of dynamic elastic multi-link structures is given. Furthermore, the control of networks of serially connected Euler–Bernoulli beams is studied in several papers, e.g., in Chen, Delfour, Krall, and Payre (1987) and Mercier and Régnier (2014). However, these contributions deal with control inputs given by forces and torques, which is not suitable for the systems under consideration.

In this paper, the linearized equations of motion for a planar manipulator composed of a finite number of linked Euler–Bernoulli beams in an arbitrary pose are systematically derived. In order to constrain the complexity of the calculation, the linearization of the system is performed at an early stage. For this purpose, a first order approximation is employed for the rotation matrices used for the description of the kinematic relations. Furthermore, it is assumed that underlying velocity controllers for the joint motion based on a servo compensation for the hydraulic actuators are implemented and thus the joint angle velocities can be considered as control inputs to the system. Application of Hamilton's principle yields the linearized partial differential equations describing the motion of the structure. In order to render the closed-loop system passive, the temporal behavior of the overall energy stored in the system is analyzed. With this, a control law is proposed, which ensures the asymptotic stability of the closed-loop system. The feasibility of the proposed control approach is demonstrated by means of measurement results for an industrial mobile concrete pump.

The paper is organized as follows: In Section 2, the essential steps for the derivation of the mathematical model are presented. The control law, detailed in Section 3, is based on the equations of motion and the energy stored in the overall system. In Section 4, the proof of the asymptotic stability of the closed-loop system is given. The practical implementation as a decentralized modular control law and its validation by means of measurement results on a mobile concrete pump are the content of Sections 5 and 6. Finally, a short conclusion is given in Section 7. The Appendices A and B contain some derivations needed for the stability proof. Note that preliminary results motivated by a single rotational beam involving pure simulation results without a stability proof are provided in Henikl, Kemmetmüller, and Kugi (2013).

2. Energy-based mathematical modeling

In the following, the essential steps for the derivation of the linearized equations of motion of a planar manipulator composed of N linked Euler–Bernoulli beams with lengths $L_n,\ n = 1, \ldots, N$ are presented. As shown in Fig. 2 for a two-link manipulator, the overall motion of the system is described with respect to the inertial frame $0_0x_0z_0$. As mentioned before, the system will be linearized around an arbitrary equilibrium. For this reason, the local coordinate frames $0_nx_nz_n$ with $n > 0$ are defined by means of the operating points ψ_n^d of the joint angles. With this, the degrees of freedom are given by the beam deflections $w_n(x_n)$, which, in addition to the elastic deformations of the beams, include the deviations of the joint angles from their operating points ψ_n^d. The joint movement can be controlled by means of hydraulic actuators comprising differential cylinders and servo valves.

Remark 1. As already discussed in the introduction, the joint angle velocities are supposed to be imposed by underlying controllers such that they may be considered as control inputs to the system.

In order to derive the equations of motion, the extended Hamilton's principle, see, e.g., Meirovitch (1990), will be applied,

$$\int_{t_0}^{t_e} [\delta(E_K - E_P) + \delta E_{NC}]\mathrm{d}t = 0, \tag{1}$$